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COMPUTER PROGRAM FOR CALCULATING DIELECTRIC PROPERTIES OF LOW- OR HIGH-LOSS MATERIALS FROM SHORT-CIRCUITED WAVEGUIDE MEASUREMENTS[1]

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A general computer program with a number of unique features was developed for precise calculation of dielectric properties of materials from measurements obtained on short-circuited coaxial, cylindrical, or rectangular waveguides. Dielectric properties of either high- or low-loss materials are correctly determined from standing-wave ratios (measured with and without the sample in the shorted end of the waveguide) and the shift of the voltage standing-wave minimum (or the current standing-wave maximum) resulting from the presence of the sample. Corrections are included for waveguide wall losses and for the influence of the slot on the guide propagation constants for rectangular and cylindrical waveguide slotted sections. Important principles of the measurement and calculation methods are outlined. Graphical illustrations and necessary mathematical relationships are presented. A listing of the program is included along with concise examples of input and output data.

INTRODUCTION

The dielectric properties of materials are important for numerous applications. In the study for which this computer program was developed, data were needed over a wide range of frequencies on the dielectric properties of grain and insects to identify the most promising frequency ranges for possible insect control by selective dielectric heating of the insects in infested grain (*8*).[4] The program and methods of measurement described here, however, are applicable to a wide range of materials. They are also useful over a wide range of frequencies where slotted-coaxial-line and slotted-waveguide measurement techniques are applicable, approximately 100 MHz to 30 GHz or higher.

The dielectric properties of interest here are the permittivity or dielectric constant, the dielectric loss factor, the loss tangent of the dielectric, and the a-c conductivity. The reader is referred to other sources for detailed conceptual information and definitions based on circuit concepts (*4*, *6*) or electromagnetic field concepts (*3*, *7*, *8*). The complex relative permittivity (complex relative dielectric constant) is represented as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' = \varepsilon_r'(1 - j \tan \delta)$, where ε_r' is the real part of the complex permittivity, frequently called the dielectric constant; the imaginary part, ε_r'', is the dielectric loss factor; and $\tan \delta = \varepsilon_r''/\varepsilon_r'$ is known as the loss tangent (also called the dissipation factor). The a-c conductivity, $\sigma = \omega\varepsilon_o\varepsilon_r''$, and ε_r'' include all energy-dissipating mechanisms observed in the dielectric as a result of its subjection to the forces of the alternating electric field. Here ε_o is the permittivity of free space, 8.854×10^{-12} farad/m., and ω represents the angular frequency, $2\pi f$, where f is frequency in Hz.

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[4] Italic numbers in parentheses refer to literature cited at the end of the report.

By using a measurement system with a slotted-line or slotted-waveguide section, it is possible to obtain information from which the dielectric properties of materials may be calculated. Roberts and von Hippel (*10*) originally reported the method used. The voltage standing-wave ratio (VSWR) in front of a sample material, placed at the end of a coaxial line or waveguide terminated in a short circuit, is determined with the sample in place. The VSWR is also measured with the sample removed. The shift in the position of the voltage minimum (node) due to the presence of the sample is also determined. This information, together with the sample dimensions, frequency, and characteristics of the waveguide, permits determination of the dielectric properties. Solution of a complex transcendental equation required the use of charts of complex hyperbolic functions or a series approximation. Dakin and Works (*2*) reported simplified calculation procedures for this method based on approximations valid for materials when $\tan \delta < 0.1$. They also included a correction for the wall losses in the waveguide in determining the loss tangent of the sample material. Westphal (*12*), who included a more precise procedure for correcting for wall losses in the waveguide, described further refinements for the method. A complete description of the principles of this method and methods of measurement and calculation, along with derivations of important equations, has been assembled in one reference (*8*). Only those relationships necessary for understanding and describing the computer program will be presented here.

PRINCIPLES OF THE MEASUREMENT METHOD

Fig. 1 represents the short-circuited end of a rectangular waveguide containing a sample of length d in contact with the short circuit. The incident wave traveling in the positive z direction and the reflected wave combine to form standing waves in the waveguide. A voltage standing-wave pattern is illustrated in fig. 2, where it may be noted that the wavelength in the sample, medium 2, is shorter than that in the empty part of the waveguide, medium 1. Voltage minima or nodes are spaced at half-wavelength intervals in the waveguide. A more general voltage standing-wave pattern is illustrated in fig. 3, where a comparison of the standing-wave pattern with and without the sample in the end of the waveguide is shown. In these figures, λ_1 represents the guide wavelength in the empty waveguide, hereinafter referred to as λ_g for conventional reasons, z_s represents the position of the voltage node with the sample in the waveguide (the sample node), and z_a represents the node position for the empty waveguide (the air node). Δz_a and Δz_s represent widths of the air and sample nodes, respectively, measured

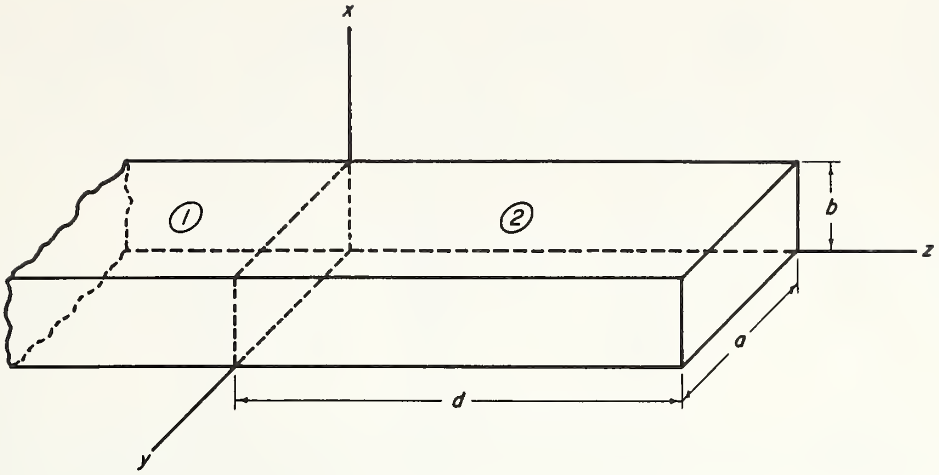

Figure 1.--Short-circuited rectangular waveguide with dielectric sample of length *d* at the shorted end.

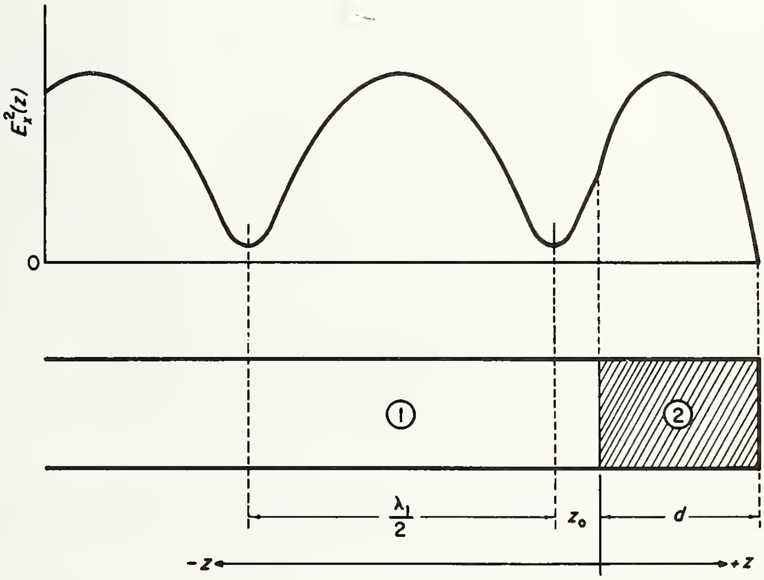

Figure 2.--Relationship of voltage standing-wave pattern to shorted waveguide with dielectric sample.

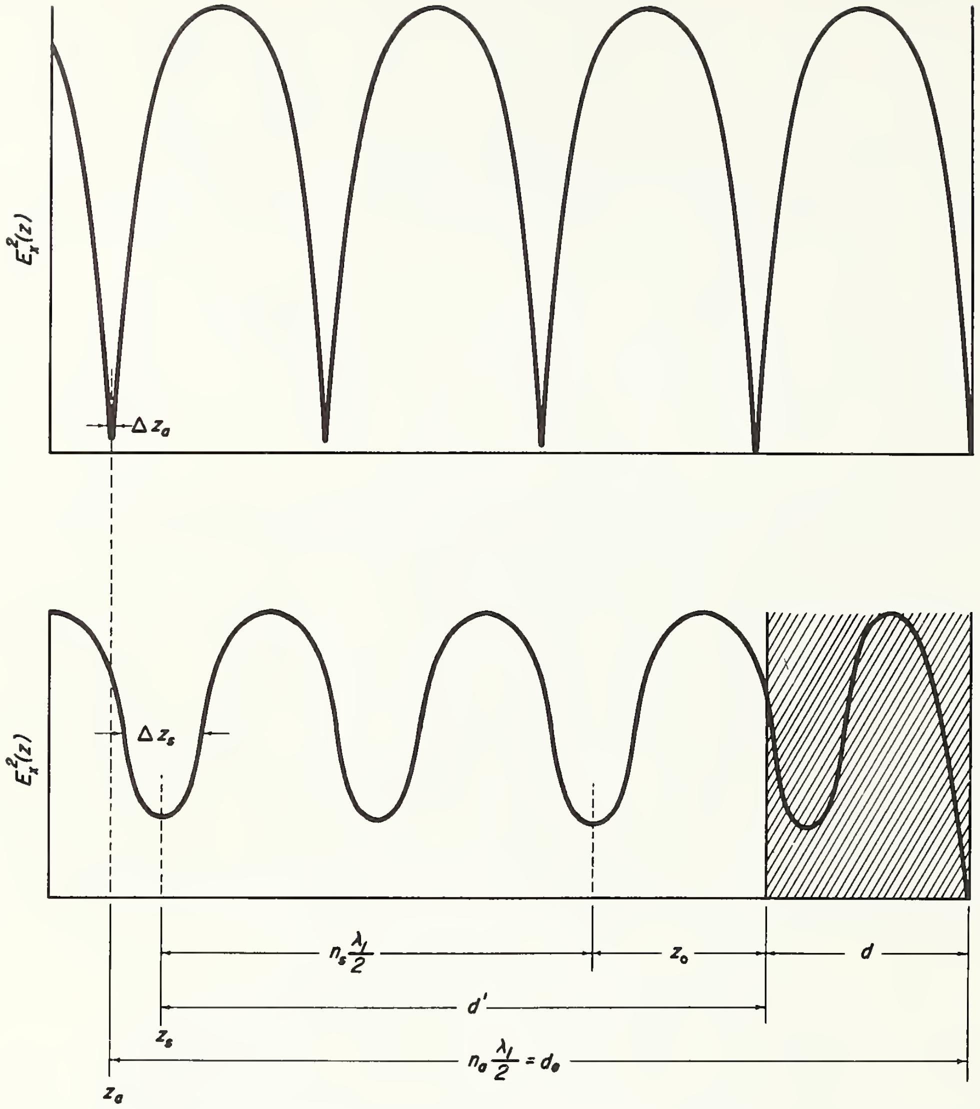

Figure 3.--Voltage standing-wave pattern relationships in empty waveguide and in waveguide with dielectric sample in place.

at specified levels above the voltage minimum, and n_a and n_s are integers. The distance from the air-sample interface to the first voltage minimum outside the sample is designated as z_0.

If, instead of a slotted line with a capacitively coupled probe, an inductively coupled loop in the plane of a movable short circuit is used, the current standing-wave pattern may be observed. In this case, the locations of the current maxima are measured and the width of the current peaks at a specified level below the maximum is used to determine the standing-wave ratio.

As already mentioned, the measurement of z_a and z_s, and the standing-wave ratios with and without the sample in place are sufficient, together with known values for d and frequency, or guide wavelength, to calculate the dielectric properties of the sample. Standing-wave ratios are obtained from the measured Δz values and the dB levels above the minimum where the node widths are measured in accordance with the following equation:

$$\frac{E_{max}}{E_{min}} = \frac{\sqrt{\left(\frac{E(z)}{E_{min}}\right)^2 - \cos^2 \frac{\pi \Delta z}{\lambda_g}}}{\sin \frac{\pi \Delta z}{\lambda_g}} = \frac{\sqrt{P_r - \cos^2 \frac{\pi \Delta z}{\lambda_g}}}{\sin \frac{\pi \Delta z}{\lambda_g}}, \qquad [1]$$

where P_r represents the power ratio corresponding to the dB level employed. It has been customary in these types of measurements to use 3-dB levels (twice-minimum-power points) for simplicity, since eq. 1 then reduces to $E_{max}/E_{min} = \sqrt{1 + \csc^2 (\pi\Delta z/\lambda_g)}$, and, if $\pi\Delta z/\lambda_g$ is small,

$$\frac{E_{max}}{E_{min}} \simeq \frac{\lambda_g}{\pi \Delta z}. \qquad [2]$$

The value for λ_g needed in eqs. 1 or 2 may be obtained by measurement of $\lambda_g/2$ with the slotted section or calculated from the frequency if the frequency is accurately known,

$$\lambda_g = \frac{\lambda_o}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}} = \frac{\lambda_o}{\sqrt{1 - \left(\frac{\lambda_o}{\lambda_c}\right)^2}}, \qquad [3]$$

where λ_o is the free-space wavelength corresponding to $f = c/\lambda_o$ (c = velocity of propagation in free space, 2.997925×10^8 m./sec.), and f_c and λ_c are the cutoff frequency and cutoff wavelength, respectively, for the waveguide ($f_c\lambda_c = c$).

For precise measurements, the influence of the slot in a slotted waveguide section must also be taken into account. Distances measured with a slotted section will be slightly too long because reflections from the slot influence the propagation constant in the guide. Corrections for this can be made using the following relationships. For rectangular waveguide propagating energy in the TE_{10} mode (*5*, *9*),

$$\lambda_{gm} = \lambda_g \left(1 + \frac{w^2 \lambda_g^2}{8\pi b a^3}\right), \qquad [4]$$

where λ_{gm} represents the measured guide wavelength, λ_g the true guide wavelength in a nonslotted section of the waveguide, w the width of the slot, and

a and b the inside dimensions of the rectangular waveguide (fig. 1). For cylindrical waveguide operating in the TE_{11} mode,[5]

$$\lambda_{gm} = \lambda_g \left\{ 1 + \frac{(w\ \lambda_g \tau)^2}{8(\pi r)^4\ (\tau^2 - 1)} \right\} = \lambda_g \left\{ 1 + \frac{0.00182\ (w\ \lambda_g)^2}{r^4} \right\}, \qquad [5]$$

where r is the inside radius of the guide and τ is the first root providing a zero value for the first derivative of the first-order Bessel function of the first kind and has the value 1.84118.

The original equations presented by Roberts and von Hippel (*10*) may be written as follows:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' = \left(\frac{\lambda_o}{\lambda_c} \right)^2 - \left(\frac{\gamma_2 d\ \lambda_o}{2\pi d} \right)^2 \qquad [6]$$

and

$$\frac{\tanh \gamma_2 d}{\gamma_2 d} = - \frac{j\lambda_g}{2\pi d} \ \frac{\dfrac{E_{min}}{E_{max}} - j \tan \dfrac{2\pi z_o}{\lambda_g}}{1 - j \dfrac{E_{min}}{E_{max}} \tan \dfrac{2\pi z_o}{\lambda_g}}, \qquad [7]$$

where ε_r is the complex dielectric constant of the sample and $\gamma_2 = \alpha_2 + j\beta_2$ is the complex propagation constant in the sample, where α and β are the attenuation and phase constants.

Values for $\gamma_2 d$ must be extracted from eq. 7 for use in eq. 6. Determination of the inverse standing-wave ratio, λ_g, z_o, and d, the length of the sample, permits the right-hand side of eq. 7 to be reduced to a complex number, $Ce^{j\zeta}$, and $\gamma_2 d$ may be obtained from charts of the complex hyperbolic function (*10*, *12*) or, in some cases, calculated from a series approximation (*10*).

The simplified equations, for the case when $\tan \delta < 0.1$, presented by Dakin and Works (*2*) may be written

$$\varepsilon_r' = \left(\frac{\lambda_o}{\lambda_c} \right)^2 + \left(\frac{\beta_2 d\ \lambda_o}{2\pi d} \right)^2 \qquad [8]$$

and

$$\frac{\tan \beta_2 d}{\beta_2 d} = - \frac{\lambda_g \tan \dfrac{2\pi z_o}{\lambda_g}}{2\pi d}. \qquad [9]$$

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[5] Personal communication, Howard E. Bussey, National Bureau of Standards, U.S. Department of Commerce, Boulder, Colorado, 1971.

Using these approximations, values for $\beta_2 d$ can be obtained more easily than $\gamma_2 d$ by reference to tables for the function $(\tan X)/X$. The dielectric constant is then obtained using eq. 8 and tan δ is given by another expression,

$$\tan\delta = \frac{\Delta z}{d}\left(1 - \frac{\lambda_o^2}{\lambda_c^2\ \varepsilon_r'}\right)\left(\frac{1 + \tan^2 \dfrac{2\pi z_o}{\lambda_g}}{1 + \tan^2 \beta_2 d - \dfrac{\tan \beta_2 d}{\beta_2 d}}\right) . \qquad [10]$$

The wall-loss correction suggested by Dakin and Works was obtained by applying eq. 10 to the empty waveguide giving

$$\tan\delta_w = \frac{\Delta z_a}{d_e}\left(1 - \frac{\lambda_o^2}{\lambda_c^2}\right), \qquad [11]$$

which is subtracted from the tan δ value obtained from eq. 10 for the sample measurement to obtain the corrected tan δ value for the sample.

A more precise correction for wall losses was described by Westphal (*12*), taking into account differences in wall losses in the sample-filled part of the guide with the sample present and with the sample absent. To correct for wall losses between the sample face and the slotted section probe, the value of Δz_s can be corrected before using it in eq. 10, or in eq. 1 for determination of inverse standing-wave ratios for use in eq. 7. The appropriate expression, referring to fig. 3, is

$$(\Delta z_s)_{corrected} = (\Delta z_s)_{measured} - \frac{d'}{d_e}\,\Delta z_a . \qquad [12]$$

The wall losses in the sample-filled part of the guide are then determined from the following relationship applicable to nonmagnetic materials,

$$\tan\delta_{ws} = \tan\delta_w \frac{C_g + \left(\dfrac{\lambda_o}{\lambda_c}\right)^2 \dfrac{1}{\varepsilon_r'}}{C_g + \left(\dfrac{\lambda_o}{\lambda_c}\right)^2} , \qquad [13]$$

where, for rectangular waveguide, $C_g = a/2b$, and, for cylindrical waveguide, $C_g = 0.42$. This term then, $\tan\delta_{ws}$, is subtracted from the tan δ value obtained from eq. 10 or from $\tan\delta = \varepsilon_r''/\varepsilon_r'$ using values obtained from eq. 6. In the latter case, a corrected ε_r'' value is then calculated as $\varepsilon_r' \tan\delta$ using the corrected value for tan δ of the sample. Losses in the short-circuit termination are usually neglected, but may need to be taken into account for measurements on extremely low-loss materials. Since these losses are difficult to describe generally, no provision for them is included in the program.

All of the foregoing equations, except eqs. 4 and 5, are also applicable to coaxial waveguide where λ_o/λ_c becomes zero, since the cutoff wavelength is infinite. The slot in a coaxial slotted section has no effect on the measured guide wavelength, so no correction for its influence is required.

The determination of z_o needed for use in eq. 7 or in eqs. 9 and 10 is found from fig. 3 to be

$$z_o = (n_a - n_s)\,\lambda_g/2 - [d + (z_a - z_s)]\ . \qquad [14]$$

Another equation from the paper of Dakin and Works (2) is used for a first approximation in the computer program,

$$\alpha_2 d = \frac{\beta_2 d\ \lambda_g}{2\pi d}\ \frac{E_{min}}{E_{max}}\ \frac{1 + \tan^2 \dfrac{2\pi z_o}{\lambda_g}}{1 + \tan^2 \beta_2 d - \dfrac{\tan \beta_2 d}{\beta_2 d}}\ . \qquad [15]$$

For high-loss materials, equations for the general case, eqs. 6 and 7, must be used to obtain valid data. Since the calculations and use of complex function charts are tedious, time-consuming, and sometimes inaccurate, a computer program was developed to handle the necessary computations.

COMPUTER PROGRAM DESCRIPTION

Main Program

The program was designed for general use and accommodates input data taken from measurements on coaxial lines, or cylindrical or rectangular waveguides. It properly performs the necessary calculations for either low-loss or high-loss dielectric samples and prints out the final values for ε_r', ε_r'', tan δ, and σ.

Calculations were programmed for computation on an IBM 360 Model 65 computer using FORTRAN IV programming language and requiring 140K storage for the GO step.* (If necessary, storage requirements could be reduced.) The program listing is shown in the appendix. A laboratory data sheet with entries for measurements is also included in the appendix. Input data are punched on three cards (fig. 4). An initial card indicates the number of data sets to be run (limit of 50).

A parameter card for each data set carries the number of samples for the data set, 40-character sample description for the data set, waveguide dimensions, a reference dimension, R, which corresponds to an approximate distance between the short-circuit termination and the slotted-line or slotted-section probe when positioned at zero on its scale, the width of the slot in the slotted section for use in correcting slotted-section wavelength data, and instructions for the detail of printout desired. For rectangular waveguides, the horizontal

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*When compiled under IBM OS/MVT, the program executes in 40K of core. Typical CPU time required for processing 50 sample measurements is less than 20 seconds. There are no files other than the input (reader) and the output (printer) files.

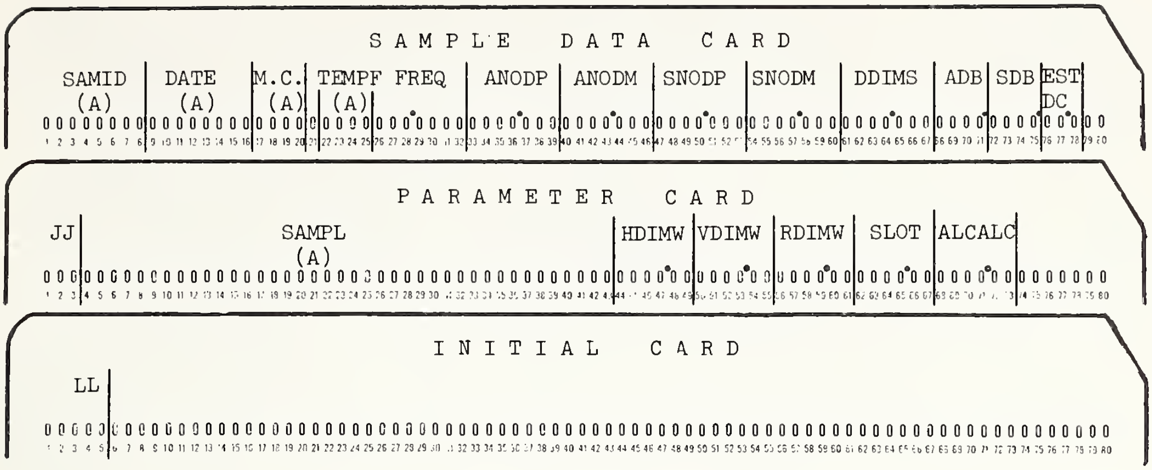

Figure 4.--Three types of input data cards for computer program, initial card, parameter card, and sample data card, showing division of fields and automatic decimal point locations.

and vertical dimensions, a and b $(a > b)$, are entered on the card. If the diameter of a cylindrical waveguide is entered in the "a-dimension" column only, the calculations are carried out for the cylindrical-waveguide case. If nothing is punched for the a and b-dimensions, the calculation proceeds for the coaxial-line case.

The third card carries the individual sample data including sample identification, date, moisture content, temperature, frequency, twice-minimum-power-point readings [or readings taken at other power-ratio levels for z_a and z_s, the air (empty-waveguide) and sample voltage nodes], the sample length, d, the dB levels used for the node width readings if other than 3-dB levels, and an estimate of the value of ε_r', the dielectric constant. All length measurements are in mm., and f is in GHz.

Provisions are made in the program for calculating frequency from adjacent node data taken on the slotted lines or slotted sections if this is more convenient or results in a more accurate frequency determination for any particular system. If frequency is to be determined in this way, an extra card is punched in accordance with the sample data card format and placed in front of the sample data cards for which this frequency applies. No entry is made in the frequency columns on this card, but data for the two adjacent air nodes are punched in the air-node and sample-node columns. No other entries are made on this card. The program then checks for the presence of data in the frequency and sample-length columns, and, if none is found, the calculation of frequency from the guide-wavelength data is performed. The check for sample-length data is necessary since data cards immediately following this card have no frequency data punched either.

For coaxial lines, frequency is simply determined as $f = 299.6966/\lambda_g$, since $\lambda_o = \lambda_g$, and $\lambda_g/2$ is the distance between adjacent nodes in the air-filled line. The constant used here represents the velocity for electromagnetic propagation in unbounded air space. Using ε_r for air = 1.00064,[6] the velocity of light in air = $c/\sqrt{\varepsilon_r}$ = 2.996966 x 10^8 m./sec., where c is the velocity of light in vacuum (2.997925 x 10^8 m./sec.). Use of the value for velocity in air provides higher accuracy in the measurement results.

For either cylindrical or rectangular waveguide, the relationship from eq. 3, $\lambda_o = \lambda_g/\sqrt{1 + (\lambda_g/\lambda_c)^2}$, must be employed to find the free-space wavelength, λ_o. Before calculating λ_o, however, the proper value for λ_g must be obtained from eqs. 4 or 5, depending upon the type of waveguide, which correct for the error in measured guide wavelength due to the influence of the slot in the slotted section.[7] Finding λ_g in eqs. 4 or 5 requires the solution to a cubic equation, so an iterative solution using Newton's approximation,

$$x_{n+1} = x_n - f(x_n)/f'(x_n) \ , \qquad [16]$$

is employed in the program. Once λ_o is found, f is calculated as $299.6966/\lambda_o$ in the same way as in the coaxial case.

Calculations then proceed, using f, whether entered directly on the data card, or calculated as just explained using adjacent node measurement data, as follows:

Wavelength in air, $\lambda_o = 299.6966/f$. Waveguide cutoff wavelength, $\lambda_c = 2a$ for rectangular guide or λ_c = 1.706293 D, where D represents diameter of cylindrical guide. Guide wavelength, $\lambda_g = \lambda_o/\sqrt{1 - (\lambda_o/\lambda_c)^2}$. Next, for the waveguide case, a correction factor for the influence of the slot on z-dimension data taken on a slotted section is calculated using eqs. 4 or 5. The air- and sample-node positions, z_a and z_s, with reference to the slotted-line or slotted-section scale zero are calculated by averaging the double-power-point readings (or readings taken at other power-ratio levels), and Δz_a and Δz_s are obtained as the absolute value of their differences, so that the order of double-power-point entries for each node on the data cards is of no importance. Δz_a and Δz_s values are then corrected for the influence of the slotted-section slot. The node shift due to the sample, $z_a - z_s$, is then calculated and corrected for the influence of the slot. At this point in the program, d_e of fig. 3, which is needed later for line and wall-loss corrections, is estimated by adding the reference dimension R (the approximate distance from the short-circuit termination to the slotted-line or slotted-section probe when set to zero on its scale) to the z_a value referenced to the scale zero. Since d_e is an integral number of half-wavelengths in the guide, the precise value for d_e is found in the program by successively adding half-wavelengths until the difference between $n \lambda_g/2$ and the estimate for d_e is less than $\lambda_g/4$. With this determination of n, d_e is set equal to $n \lambda_g/2$.

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[6] The value of ε_r for air at 20° C. and 760 mm. Hg pressure with a dew-point temperature of 9° C. (*1*). The equation for ε_r used by Brady (*1*) was originally produced by Smith and Weintraub (*11*), since $\varepsilon_r = n^2$, where n is the index of refraction. Their equation was $n = \frac{77.6}{T}\left\{p + 4810\,\frac{e}{T}\right\}$, where T is the absolute temperature in degrees K, p is the total pressure in millibars, and e is the partial pressure of water vapor in millibars. The elevation at Lincoln, Nebr., is about 1,200 feet above sea level, and the corresponding mean atmospheric pressure is 730 mm. Hg. Under these conditions, at 40-percent relative humidity and 76° F., the equation gives $n^2 = \varepsilon_r$ = 1.00061. Since the difference between $\sqrt{1.00064}$ and $\sqrt{1.00061}$ is less than 2 x 10^{-5}, no correction for the 1,200-ft. difference in elevation or 8°-F. difference in temperature was justified in this study.

[7] If slot dimensions are not entered on the parameter card, the program automatically inserts values for the equipment used in this study, 3.2 mm. for rectangular guide and 1.24 mm. for cylindrical guide.

Next, the provision for using other than 3-dB points (twice-minimum-power points) for the node-width measurement is considered. If no entry is punched in the dB-level columns of the data card, the program automatically inserts 3 dB. The usual procedure is to use 3-dB levels to simplify calculations. However, better accuracy may be provided by using levels greater than 3 dB for very high standing-wave ratios, and, in practice, some samples were found to provide such a good impedance match that 3-dB levels could not be used because E^2_{min} was less than 3 dB below E^2_{max}. Therefore, the calculations are programmed to provide for any possible dB level in measuring Δz_a and Δz_s. Since a greater dB level will always be possible for the air-node measurement, the program converts the Δz_a value to the proper value for the dB level used for the measurement of Δz_s if they are measured at different dB levels. Eq. 1 provides a value for the VSWR for any dB level or power ratio. The dB level is converted to power ratio, $P_r = [E(z)/E_{min}]^2$, as follows for use in eq. 1: $\text{dB} = 10 \log_{10} P_r = (10 \ln P_r)/(\ln 10)$, so $P_r = e^{0.2302585(\text{dB})}$. After finding the VSWR value from eq. 1, the Δz_a value corresponding to the dB level at which Δz_s was measured is obtained by solving eq. 1 for Δz_a using P_r for the sample dB level.

Since Δz_s must be corrected for guide or line losses between the sample and the probe, the ratio d'/d_e (see fig. 3) is calculated and used in eq. 12 to provide the value of Δz_s corrected for these losses. The inverse standing-wave ratio with the sample in the guide is then calculated using eq. 1.

Next, the program calculates z_o according to eq. 14 by successively adding half-wavelengths to $-[d + (z_a - z_s)]$, if it is not already positive, until the result is positive. If a sample-node position is used which is farther away from the short circuit than the air-node position, $(z_a - z_s)$ will have a negative value, and if $|z_a - z_s|$ exceeds d, the quantity $-[d + (z_a - z_s)]$ will be positive. This value is then taken for z_o in the program. Even if a sample node should be selected which is more than $\lambda_g/2$ beyond the air node, the value obtained in this way for z_o will work all right in the program, since $\tan (2\pi z_o/\lambda_g)$ is equivalent to $\tan [2\pi(z_o + \lambda_g/2)/\lambda_g]$ as a consequence of the identity, $\tan(\theta + \pi) = \tan\theta$. Thus, any air node and any sample node, without reference to relative position or distance apart, will suffice for the measurement.

In order to use eq. 7 for computation, the right-hand side must be rationalized and separated into its real and imaginary components. This may be rewritten

$$\frac{\tanh \gamma_2 d}{\gamma_2 d} = Ce^{j\zeta} = \frac{\lambda_g \tan U(\phi^2 - 1) - j\,\lambda_g\,\phi(1 + \tan^2 U)}{2\pi d(1 + \phi^2 \tan^2 U)} = \frac{\lambda_g(A - jB)}{2\pi d(1 + \phi^2 \tan^2 U)}, \quad [17]$$

where ϕ represents the inverse standing-wave ratio and U represents $(2\pi\, z_o)/\lambda_g$. For computer solution, close estimates for the components of $\gamma_2 d = \alpha_2 d + j\beta_2 d$ are needed and then they can be adjusted until eq. 17 is satisfied. For given values of $\alpha_2 d$ and $\beta_2 d$, an expansion of $(\tanh \gamma_2 d)/\gamma_2 d$ is used to calculate real and imaginary parts in a subroutine called ACOMP.

An initial estimate of $\beta_2 d$ is obtained from eq. 8, which is valid for the low-loss case, by solving for $\beta_2 d$ using the estimated value from the data input for ε_r'. In the program, if no value is entered on the parameter card for the estimated dielectric constant, a value of 2.5 is automatically taken. Provision is also made in the program to use the dielectric constant calculated for the previous sample as the estimated dielectric constant for the next sample in a series of similar samples if no estimated value is punched on the data card. Since, in the lossless case, $\alpha_2 = 0 = \zeta$, $(\tanh \gamma_2 d)/\gamma_2 d = Ce^{j\zeta}$ becomes, in accord with eq. 9, $(\tan \beta_2 d)/\beta_2 d = C$. C is calculated as the magnitude of the right-hand side of eq. 17 because, for lossy dielectric samples, C will include a contribution due to the loss and will provide a better estimate for $\beta_2 d$ than might be obtained using eq. 9.

On certain usually rare occasions, the sample may turn out to be very nearly an odd multiple quarter-guide-wavelength in the sample material. In this case, z_o is nearly a quarter-guide-wavelength, so $\tan U = \tan(2\pi\, z_o/\lambda_g)$ takes on very large values, and subsequent calculations involving the hyperbolic functions of $\alpha_2 d$ and $\beta_2 d$ exceed the capacity of the computer. Therefore, a test was inserted in the program, and, if $\tan U$ exceeds a value of 200, it branches to a later point in the program, where an approximate value for the dielectric constant is calculated using eq. 8 and the value of $\beta_2 d$ arrived at by the FUNCTION FINDX subroutine to be described later. A statement then appears in the printout, "Bad sample length for this frequency, nearly an odd multiple quarter-wavelength," and zeros are printed out for the loss tangent, loss factor, and conductivity.

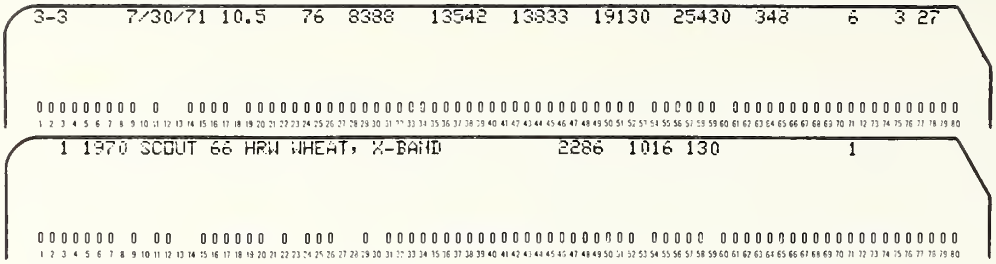
In the usual case where $\tan U$ does not exceed a value of 200, the estimate of $\beta_2 d$ is then improved by adjusting it to satisfy $(\tan \beta_2 d)/\beta_2 d = C$ in the subroutine, FUNCTION FINDX. This value of $\beta_2 d$ and a value for $\alpha_2 d$, calculated from eq. 15 using this improved estimate of $\beta_2 d$, then comprise the first estimate for $\gamma_2 d$. These unadjusted values for $\alpha_2 d$ and $\beta_2 d$ are printed out as diagnostics immediately following the first estimate of $\beta_2 d$. The components $\alpha_2 d$ and $\beta_2 d$ are then adjusted in a subroutine called ADJUST, to be explained later, until eq. 17 is satisfied to within a desired limit. The adjusted values of $\alpha_2 d$ and $\beta_2 d$ are also printed out along with the unadjusted values.

Since $(\tan \beta_2 d)/\beta_2 d$ and $(\tanh \gamma_2 d)/\gamma_2 d$ are ~~multivalued~~ transcendental functions and each solution to eqs. 7 and 9 results in a different set of values for ε_r' and ε_r'', the program finds three sets of $\alpha_2 d$ and $\beta_2 d$ satisfying eqs. 7 or 17 from which to proceed with the calculations. The relative permittivity or dielectric constant and the relative dielectric loss factor of the sample are then calculated from an expansion of eq. 6,

$$\varepsilon_r' - j\varepsilon_r'' = P - \left\{\frac{(\alpha_2 d + j\beta_2 d)\,\lambda_o}{2\pi d}\right\}^2 = P - S^2[(\alpha_2 d)^2 - (\beta_2 d)^2] + j\,S^2\,2\,\alpha_2 d\,\beta_2 d,$$

where $P = (\lambda_o/\lambda_c)^2$ and $S = \lambda_o/2\pi d$. The associated loss tangent for each of the three sets of values for ε_r' and ε_r'' is calculated ($\tan \delta = \varepsilon_r''/\varepsilon_r'$). The correction for wall losses with the sample present in the guide, $\tan \delta_{ws}$, is then calculated using eq. 13, after getting $\tan \delta_w$ using eq. 11, and $\tan \delta_{ws}$ is subtracted from $\tan \delta$ to give the corrected value for $\tan \delta$. Using this corrected value, a corrected ε_r'' is found as the product of ε_r' and the corrected $\tan \delta$. The three sets of dielectric properties are printed out along with important input data and a few diagnostics, unless this printout is suppressed by instructions on the parameter card, that is, nothing punched in columns 68 to 73. The program selects the probable value of ε_r', that which is closest to the estimated value for ε_r' from the input data, and, at the end of the calculations for a given data set, prints out a summary table including description, date, moisture content, temperature, sample identification, frequency, and values for ε_r', ε_r'', $\tan \delta$, and conductivity, calculated as $\sigma = \omega\,\varepsilon_o\,\varepsilon_r'' = 0.55668 f\,\varepsilon_r''$ for σ in millimhos/cm^{-1}. Examples of the input card data and printout for rectangular and cylindrical waveguide and coaxial line cases are shown in figs. 5, 6, and 7. The summary table printout is shown in fig. 8.

It should be noted that the relationship of eq. 2 based on twice-minimum-power or 3-dB points is used in the derivation of eqs. 10 and 11. Therefore, in this program, the wall-loss correction for the sample-filled part of the waveguide, $\tan \delta_{ws}$ of eq. 13, is also based on the assumption of a 3-dB air-node measurement. Since the program automatically converts the dB level for the air-node measurement to that used for the sample-node measurement, sample-node measurements on very low-loss materials, where the wall-loss correction is important, should probably be performed using the 3-dB level. In practice, the need for less than 3-dB sample-node measurements was encountered only with high-loss materials where the wall-loss correction was insignificantly small anyway. Therefore, the 3-dB level requirement for sample-node measurements is only necessary when working with very low-loss materials.

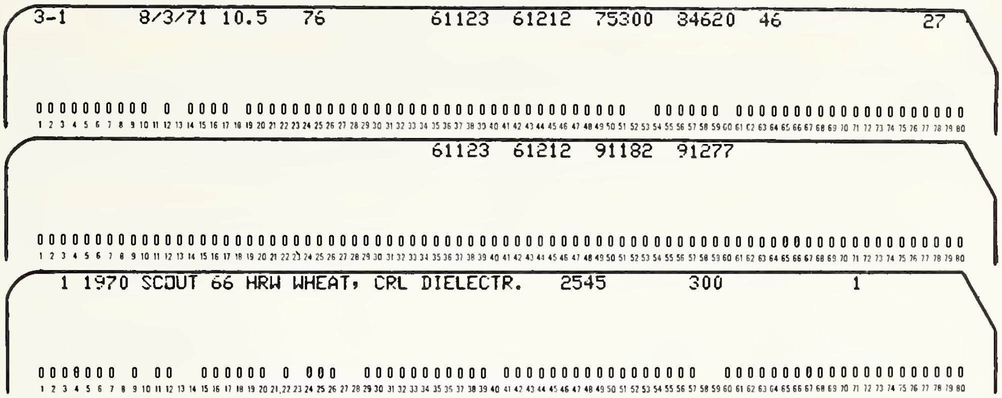


```
3-3      7/30/71 10.5   76  8388    13542  13833  19130  25430  348      6   3 27
```

```
  1 1970 SCOUT 66 HRW WHEAT, X-BAND              2286  1016 130             1
```

```
  DIELECTRIC PROPERTIES FOR  1970 SCCUT 66 HRW WHEAT, X-8AND

  RUN   1      7/30/71


MOISTURE CONTENT                                    10.5
TEMPERATURE (CEGREES FAHRENHEIT)                    76
FREQUENCY (GIGAHERTZ)                                8.3880
WAVEGUIDE HORIZONTAL DIMENSION (MM)                 22.8600
WAVEGUIDE VERTICAL DIMENSION (MM)                   10.1600
SAMPLE LENGTH (MM)                                  34.8000
AIR NODE POSITICN (MM)                              13.6875
SAMPLE NODE POSITION (MM)                           22.2800
AIR NODE WIDTH (MM)           6.0 C8                 0.2910
SAMPLE NODE WIDTH (MM)        3.0 CB                 6.3000
          REFERENCE DIMEKSION (MM)                 130.0000
ESTIMATED DIELECTRIC CONSTANT                        2.7000
FIRST ESTIMATE OF B2D (ESTX)                         5.7042

UNADJUSTED A2D, 82C                0.33920              5.73540
ADJUSTED A2D, B2D                  0.42670              5.82789

                    SAMPLE  3-3        RESULTS

DIELECTRIC CONSTANT               1.512730        2.624163        4.204988
LOSS TANGENT                      0.087389        0.091700        0.075326
LOSS FACTOR                       0.132196        0.240635        0.316744
CONDUCTIVITY                      0.617282        1.123630        1.479012



DIELECTRIC PRCPERTIES FOR  1970 SCOUT 66 HRW WHEAT, X-BAND


                             SUMMARY TA8LE

  DATE      MOIST TEPP    SAMPLE     FREQ. DIELECTRIC  LOSS    LOSS    CONDUCTIVITY
            CONT. (F.)    ICENT.     (GHZ)  CONSTANT  FACTOR TANGENT MILLIMHOS/CM

7/30/71     10.5     76   3-3        8.388    2.6242  0.2406  0.0917       1.1236
```

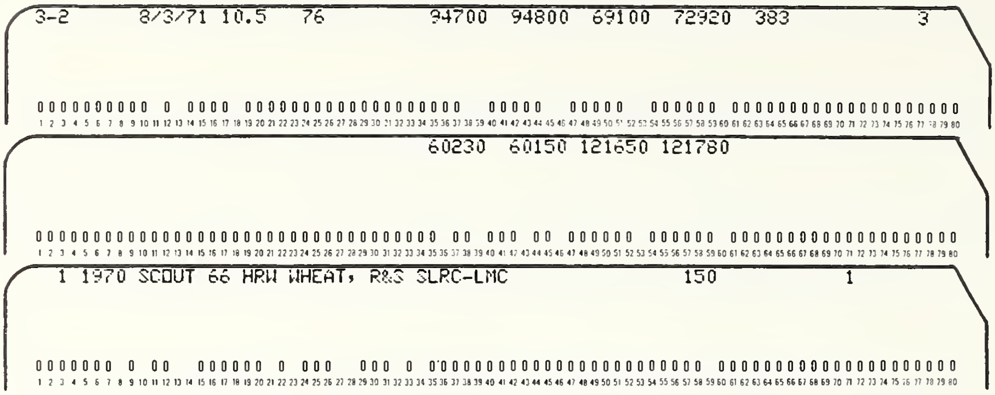
Figure 5.--Parameter card and sample data card input with printout for a rectangular waveguide measurement.



```
3-1       8/3/71 10.5   76          61123  61212  75300  34620  46              27
                                    61123  61212  91182  91277
  1 1970 SCOUT 66 HRW WHEAT, CRL DIELECTR.   2545         300            1
```

```
DIELECTRIC PROPERTIES FOR  1970 SCOUT 66 HRW WHEAT, CRL DIELECTR.

RUN   1      8/3/71


MOISTURE CONTENT                                      10.5
TEMPERATURE (DEGREES FAHRENHEIT)                      76
FREQUENCY (GIGAHERTZ)                                  8.5144
WAVEGUIDE HORIZONTAL DIMENSION (MM)                   25.4500
WAVEGUIDE VERTICAL DIMENSION (MM)                      0.0
SAMPLE LENGTH (MM)                                    46.0000
AIR NODE POSITICN (MM)                                61.1675
SAMPLE NODE POSITION (MM)                             79.9600
AIR NODE WIDTH (MM)          3.0 DB                    0.0890
SAMPLE NODE WIDTH (MM)       3.0 CB                    9.3200
          REFERENCE DIMENSION (MM)                   300.0000
ESTIMATED DIELECTRIC CONSTANT                          2.7000
FIRST ESTIMATE OF B2D (ESTX)                           8.5951

UNADJUSTED A2C, B2C                0.42110              8.67469
ADJUSTED A2D, B2D                  0.61110              8.69968


                  SAMPLE  3-1       RESULTS

DIELECTRIC CONSTANT               1.773952        2.641019        3.794526
LOSS TANGENT                      0.088833        0.077709        0.059573
LOSS FACTOR                       0.157586        0.205232        0.226052
CONDUCTIVITY                      0.746929        0.972763        1.071445



DIELECTRIC PROPERTIES FOR  1970 SCOUT 66 HRW WHEAT, CRL DIELECTR.


                         SUMMARY TABLE

  DATE     MOIST TEMP   SAMPLE    FREQ. DIELECTRIC  LOSS   LCSS   CONDUCTIVITY
           CONT. (F.)   ICENT.    (GHZ)  CONSTANT  FACTOR TANGENT MILLIMHOS/CM

8/3/71     10.5    76  3-1        8.514   2.6410   0.2052  0.0777     0.9728
```

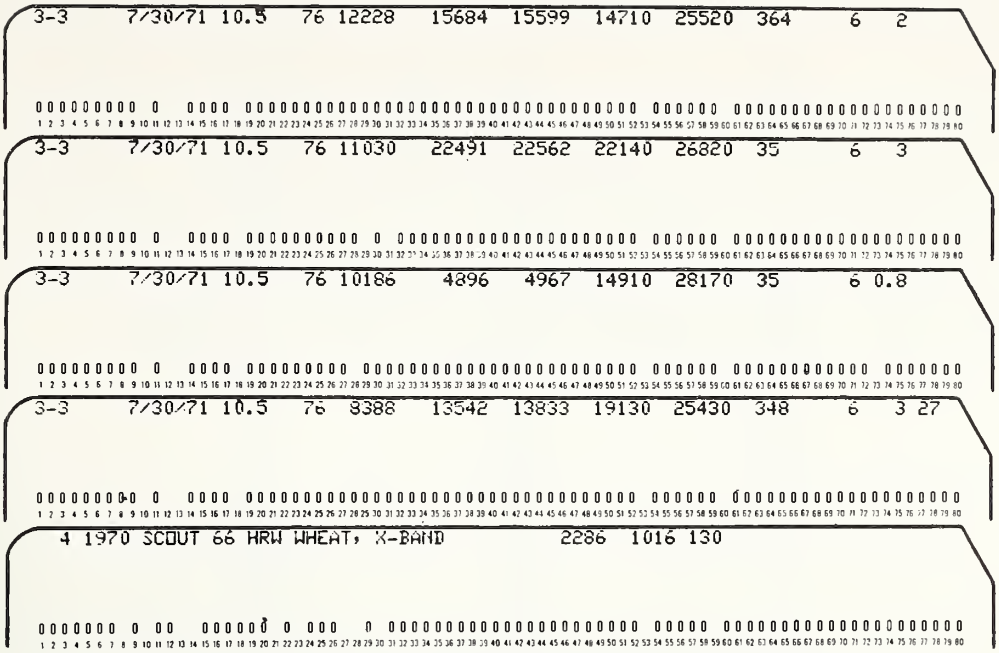
Figure 6.--Parameter card and sample data card input with printout for a cylindrical waveguide measurement, using guide-wavelength data for the frequency input.



```
3-2      8/3/71 10.5   76         94700  94800  69100  72920  383           3

                                  60230   60150 121650 121780

  1 1970 SCOUT 66 HRW WHEAT, R&S SLRC-LMC                  150          1
```

```
  DIELECTRIC PROPERTIES FOR  1970 SCOUT 66 HRW WHEAT, R&S SLRC-LMC

  RUN   1      8/3/71


MOISTURE CONTENT                                          10.5
TEMPERATURE (DEGREES FAHRENHEIT)                          76
FREQUENCY (GIGAHERTZ)                                      2.4356
WAVEGUIDE HORIZONTAL DIMENSION (MM)                        0.0
WAVEGUIDE VERTICAL DIMENSION (MM)                          0.0
SAMPLE LENGTH (MM)                                        38.3000
AIR NODE POSITION (MM)                                    94.7500
SAMPLE NODE POSITION (MM)                                 71.0100
AIR NODE WIDTH (MM)           3.0 DB                       0.1000
SAMPLE NODE WIDTH (MM)        3.0 DB                       3.8200
          REFERENCE DIMENSION (MM)                       150.0000
ESTIMATED DIELECTRIC CONSTANT                              3.0000
FIRST ESTIMATE OF B2D (ESTX)                               3.3873

UNADJUSTED A2D, B2D                  0.16494          3.30719
ADJUSTED A2D, B2D                    0.15744          3.17719


                    SAMPLE  3-2       RESULTS

DIELECTRIC CONSTANT                2.632839      10.549779      23.807678
LOSS TANGENT                       0.098944       0.101583       0.105471
LOSS FACTOR                        0.260504       1.071676       2.511011
CONDUCTIVITY                       0.353200       1.453012       3.404506



DIELECTRIC PROPERTIES FOR  1970 SCOUT 66 HRW WHEAT, R&S SLRC-LMC


                                 SUMMARY TABLE

  DATE      MOIST TEMP   SAMPLE    FREQ. DIELECTRIC  LOSS    LOSS   CONDUCTIVITY
            CONT. (F.)   IDENT.    (GHZ)  CONSTANT  FACTOR TANGENT MILLIMHOS/CM

 8/3/71     10.5    76  3-2        2.436   2.6328  0.2605  0.0989      0.3532
```

Figure 7.--Parameter card and sample data card input with printout for a coaxial line measurement, using guide-wavelength data for the frequency input.



```
3-3      7/30/71 10.5   76 12228   15684  15599  14710  25520  364      6   2
3-3      7/30/71 10.5   76 11030   22491  22562  22140  26820  35       6   3
3-3      7/30/71 10.5   76 10186    4896   4967  14910  28170  35       6 0.8
3-3      7/30/71 10.5   76  8388   13542  13833  19130  25430  348      6   3 27
  4 1970 SCOUT 66 HRW WHEAT, X-BAND             2286   1016 130
```

```
DIELECTRIC PROPERTIES FOR  1970 SCOUT 66 HRW WHEAT, X-BAND


                              SUMMARY TABLE

  DATE      MOIST TEMP   SAMPLE    FREQ. DIELECTRIC  LOSS    LOSS   CONDUCTIVITY
            CONT. (F.)   ICENT.    (GHZ)  CONSTANT  FACTOR TANGENT MILLIMHOS/CM

7/30/71     10.5    76  3-3        8.388   2.6242  0.2406  0.0917        1.1236
7/30/71     10.5    76  3-3       10.186   2.6005  0.2582  0.0993        1.4643
7/30/71     10.5    76  3-3       11.030   2.5864  0.2784  0.1076        1.7095
7/30/71     10.5    76  3-3       12.228   2.5174  0.2143  0.0851        1.4590
```

Figure 8.--Parameter card and sample data card input with summary printout only for series of rectangular waveguide measurements.

Program Subroutines

FUNCTION FINDX

In the main program, an estimate for $\beta_2 d$ is obtained using eq. 8. The FORTRAN FUNCTION FINDX is used to solve $(\tan \beta_2 d)/(\beta_2 d) = C$ for $\beta_2 d$ when C is known from measurements data. In the program, X is used to represent $\beta_2 d$. Because of the nature of the $(\tan X)/X$ function, some care must be exercised to obtain desired solutions by iterative techniques. A plot of this function is shown in fig. 9 for the range $0 \leq X \leq 3\pi$. For $(\tan X)/X = C$, it is obvious that no solutions can exist in the first quadrant for $C < 1$. For a given value of C, there are many values of X which will satisfy the equation.

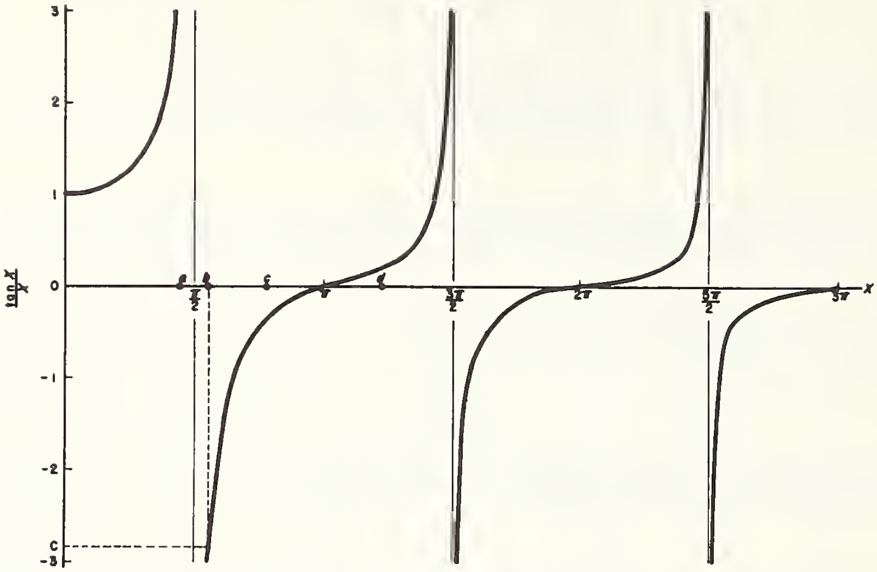


Figure 9.--Graph of the function (tan *X*)/*X*.

The program calculates and prints out dielectric properties corresponding to three different values for *X*, or $\beta_2 d$, one nearest the value derived from the estimated dielectric constant of the input data, and one on either side of this value if possible. If the estimated value of *X* obtained from eq. 8 is greater than π, π is subtracted from this value to obtain the estimated *X* value on the lower side of the original *X* estimate. If this results in a value for *X* in the first quadrant, the program checks to see whether $C \leq 1$, and, if it is, π is added back on to take the estimated *X* into the third quadrant where a possible solution exists. If the estimated *X* does not lie in the first quadrant, or, if it does, but $C > 1$, this value is taken for the first set of calculations and stored for printout as the estimated $\beta_2 d$ diagnostic immediately following the printout of input data. The program then sets $\beta_2 d$ = FINDX which is a function of C with proper sign and the estimated value of *X*.

The FUNCTION FINDX subroutine finds the value of *X* satisfying (tan *X*)/*X* = C in the following way: First, the quadrant containing the estimated *X* is identified and appropriate limits are established within which the search for the proper value of *X* will be carried out. A test is also made to determine whether C and (tan *X*)/*X* have the same sign. If they do not, and the value of *X* lies near an asymptote (ascertained by $|C| > 2$), the estimated *X* is shifted to the other side of the asymptote a distance equal to its distance from the asymptote (points *a* and *b*, fig. 9). This will change the sign of *X* thereby giving C and (tan *X*)/*X* the same sign so that a solution will be possible. New limits for the search are also then established (π/2 and 3π/2 for point *b*, for example). If the sign of C and that of (tan *X*)/*X* do not agree and the estimated X is not near an asymptote ($|C| \leq 2$), the estimated X is shifted to the other side of $n\pi$, in which quadrant a solution can be found (points c and d, for example).

An iterative technique employing Newton's successive approximation method, eq. 16, is then used to find the proper value of X satisfying $(\tan X)/X = C$. Here $f(x) = (\tan X - CX)/X$ and $f'(x) = (X \sec^2 X - \tan X)/X^2$ so that $f(x)/f'(x) = X(\tan X - CX)/(X \sec^2 X - \tan X)$. It may happen that the value of X_2 obtained using the estimated X value for X_1 in eq. 16 will fall outside the prescribed limits. For example, a solution is needed between $A = \pi/2$ and $B = 3\pi/2$ in fig. 10 and the first value obtained for $X_2 > 3\pi/2$. The program, therefore, rejects X_2 outside the prescribed region and sets the new estimate of X equal to $(X_1 + 3\pi/2)/2$ and proceeds until X_2 falls within the prescribed limits. Successive approximations then proceed until the difference between two successive approximations of X is less than 0.0001 and the program then sets the last value for X = FINDX.

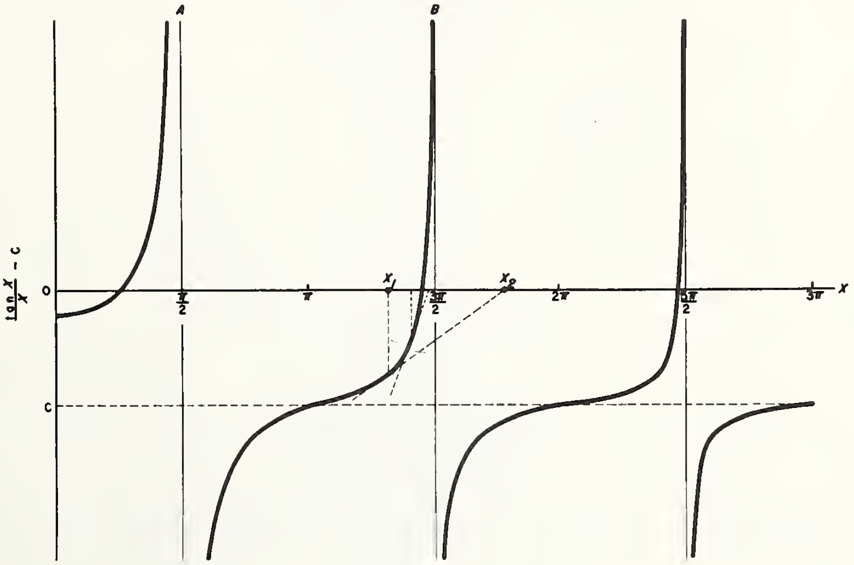


Figure 10.--Graph of the function $(\tan X)/X - C$ showing limits for successive approximation solution.

ADJUST

Following the use of the FUNCTION FINDX subroutine to improve the estimate of $\beta_2 d$ and the subsequent calculation of an estimate for $\alpha_2 d$, the ADJUST subroutine is used to adjust the values of the components of $\gamma_2 d = \alpha_2 d + j\beta_2 d$ to satisfy eq. 17. Here U_0 and V_0 represent the real and imaginary parts of the right-hand side of eq. 17, and their values are determined by measurement data. The subroutine ACOMP provides values for $(\tanh \gamma_2 d)/\gamma_2 d = U_a + V_a$ from the initial $\alpha_2 d$ and $\beta_2 d$ values calculated. The ADJUST subroutine

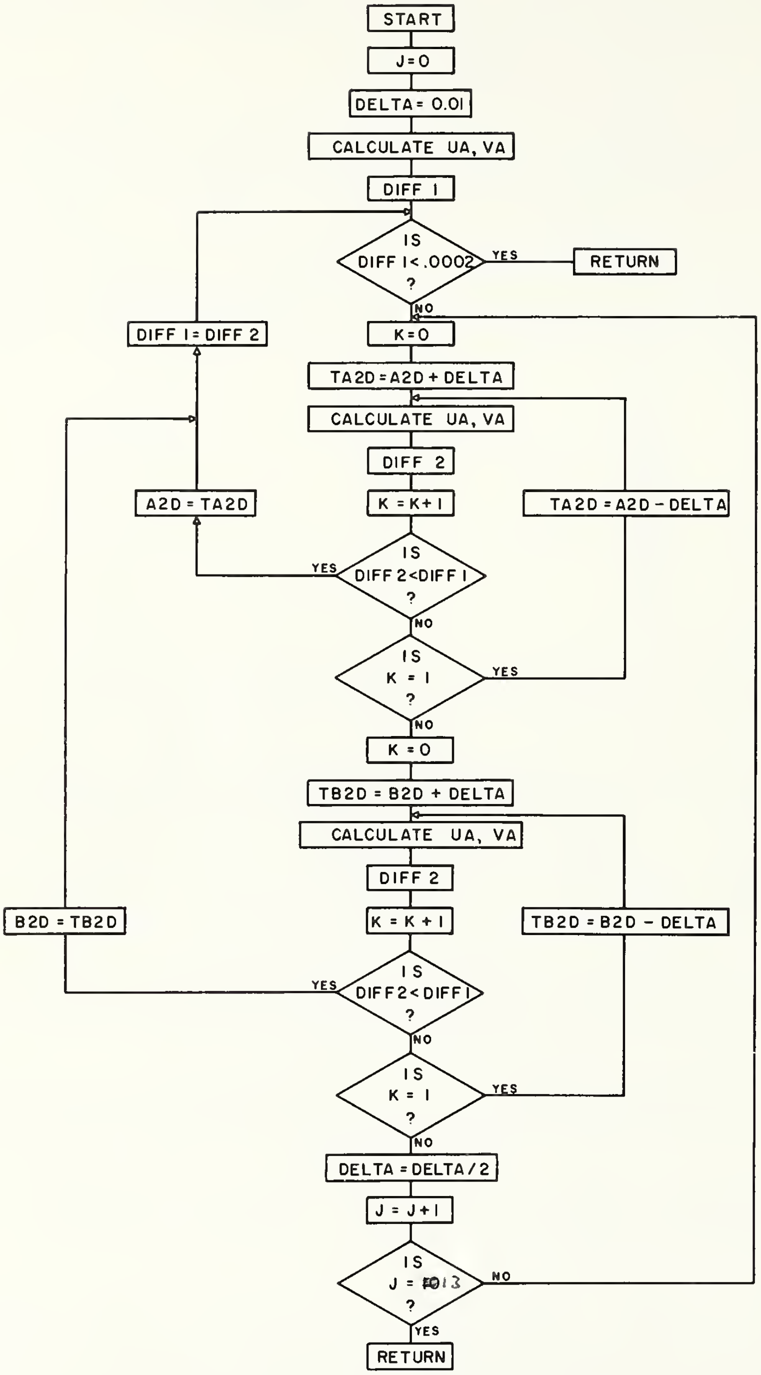


Figure 11.--Flow chart for the ADJUST subroutine.

alternately adjusts values of $\alpha_2 d$ and $\beta_2 d$ by an increment, delta, and tests to see whether the resulting $U_a + jV_a$ is approaching the desired value of $U_o + jV_o$. This is done by calculating the difference in the two-space vectors, $U_o + jV_o$ and $U_a + jV_a$, $\sqrt{(U_o - U_a)^2 + (V_o - V_a)^2}$, and requiring that this value decrease as adjustments are made. When no further improvement can be found by either positive or negative additions of delta to $\alpha_2 d$ and $\beta_2 d$, the value of delta is halved, and the adjusting procedure repeated. This reduction of delta and adjusting of $\alpha_2 d$ and $\beta_2 d$ values continues in accordance with the flow chart of fig. 11 until the magnitude of the vector difference is less than 0.0002, or until the delta value has been halved 12 times, when it returns to the main program. If the vector difference is not reduced to a value less than 0.0002, the value of the difference, called DIFF1 in the program, is printed out and identified with one of the three dielectric-constant determinations to which it applies.

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APPENDIX

Computer Program Listing

```
C      LATEST REVISION MADE AUGUST 10, 1971.  SHORTLIN
C    MAIN PROGRAM FOR CALCULATING DIELECTRIC PROPERTIES FROM
C    SHORT-CIRCUITED COAXIAL-LINE OR WAVEGUIDE MEASUREMENTS
C   INPUT DATA DESCRIPTION
C         LL         NUMBER OF SETS OF DATA
C         JJ         NUMBER OF READINGS PER SET
C         SAMPL      DESCRIPTION OF THE DATA SET,  40 SPACES
C         HDIMW      HORIZONTAL DIMENSION OF THE WAVEGUIDE IF RECTANGULAR
C                    DIAMETER OF THE WAVEGUIDE IF CIRCULAR
C                    ZERO FOR COAXIAL WAVEGUIDE
C         VDIMW      VERTICAL DIMENSION OF THE WAVEGUIDE IF RECTANGULAR
C                    ZERO OTHERWISE
C         RDIMW      WAVEGUIDE REFERENCE DIMENSION, MEASURED FROM THE
C                    SHORT TO THE 0 MM. REFERENCE POINT OF THE PROBE.
C         SLOT       WIDTH OF SLOT IN SLOTTED SECTION
C         ALCALC     ANY POSITIVE NUMBER IF COMPLETE RESULTS ARE TO BE
C                    PRINTED
C                    ZERO IF SUMMARY TABLE ONLY IS DESIRED
C         SAMID      INDIVIDUAL SAMPLE DESCRIPTION, 8 SPACES
C         DATE       E.G. 12-25-70
C         MC         MOISTURE CONTENT OF SAMPLE, 4 SPACES
C         TEMPF      SAMPLE TEMPERATURE IN DEG. FAHRENHEIT, 4 SPACES
C         FREQ       FREQUENCY IN GIGAHERTZ
C         ANODP      AIR NODE PLUS HALF NODE WIDTH
C         ANODM      AIR NODE MINUS HALF NODE WIDTH
C         SNODP      SAMPLE NODE PLUS HALF NODE WIDTH
C         SNODM      SAMPLE NODE MINUS HALF NODE WIDTH
C         DDIMS      DEPTH OF THE SAMPLE
C         ADB        DB LEVEL FOR AIR-NODE MEASUREMENT
C         SDB        DB LEVEL FOR SAMPLE-NODE MEASUREMENT
C         ESTDC      ESTIMATED DIELECTRIC CONSTANT
C         WL         WAVELENGTH IN FREE SPACE
C         WLC        CUTOFF WAVELENGTH
C         WLG        WAVELENGTH IN THE WAVEGUIDE
C   ALL MEASUREMENTS ARE IN MILLIMETERS
C
      REAL MC,LTW,LTWS
      DIMENSION ALPHA(3),BETA(3),DC(3),ALT(3),FACTOR(3),SDC(50),SLT(50),
     *  SFACT(50),SCOND(50),SF(50),STF(50),SAMPL(10),SAMID(2),  DATE(2),
     *SDAY(50,2),SSMP(50,2),SMC(50),DIFF(3),COND(3)
      IREAD=5
      IRITE=6
      TNU=0
      ESTEPM=2.5
C
      PI=3.141592654
      READ(IREAD,300) LL
  300 FORMAT(I5)
      DO 500 L=1,LL
      WRITE(IRITE,1200)
 1200 FORMAT(1H1)
      READ(IREAD,305) JJ,SAMPL,HDIMW,VDIMW,RDIMW,SLOT,ALCALC
  305 FORMAT(I3,10A4,5F6.2)
      SLOTC=1
      IF (SLOT.EQ.0.AND.HDIMW.GT.0.AND.VDIMW.GT.0) SLOT=3.20
      IF (SLOT.EQ.0.AND.HDIMW.GT.0.AND.VDIMW.EQ.0) SLOT=1.24
      IF (HDIMW.GT.0.AND.VDIMW.GT.0) WLC=HDIMW*2
      IF (HDIMW.GT.0.AND.VDIMW.EQ.0) WLC=HDIMW*1.706293
      DO 400 J=1,JJ
      DATA=0
   22 READ(IREAD,311)SAMID,DATE,MC,TEMPF,FREQ,ANODP,ANODM,SNODP,SNODM,DD
     *IMS,ADB,SDB,ESTDC
  311 FORMAT(2A4,2A4,A4,1X,A4,F7.4,5F7.3,2F4.0,F3.1)
      TF=TEMPF
      IF (FREQ.GT.0.AND.DDIMS.GT.0) GO TO 56
      IF (FREQ.EQ.0.AND.DDIMS.GT.0) GO TO 54
C
   50 WLG=ABS(ANODP+ANODM-SNODP-SNODM)
      IF (HDIMW.EQ.0) GO TO 53
      IF (VDIMW.EQ.0) GO TO 43
      WLGN=WLG
   51 CUBIC=SLOT**2*WLGN**3+8*PI*VDIMW*HDIMW**3*(WLGN-WLG)
      CUBPM=3*SLOT**2*WLGN**2+8*PI*VDIMW*HDIMW**3
      GO TO 45
   43 WLGN=WLG
      FOFAW=1.41842*SLOT**2/(8*(PI*HDIMW/2)**4)
   44 CUBIC=FOFAW*WLGN**3+WLGN-WLG
      CUBPM=3*FOFAW*WLGN**2+1
   45 WLGN1=WLGN-CUBIC/CUBPM
      IF (ABS(WLGN1-WLGN).LE.0.0001) GO TO 52
      WLGN=WLGN1
      IF (VDIMW.EQ.0) GO TO 44
      GO TO 51
   52 WLG=WLGN1
   53 IF (HDIMW.GT.0) WLG=WLG*WLC/SQRT(WLG**2+WLC**2)
      F=299.6966/WLG
      GO TO 22
   54 FREQ=F
   56 F=FREQ
      IF (FREQ.GT.0.1.AND.FREQ.LT.13) GO TO 58
  315 DATA=1
      GO TO 350
   58 WL = 299.6966/FREQ
      IF (HDIMW.EQ.0.AND.VDIMW.EQ.0) WLG=WL
      IF (HDIMW.GT.0) WLG=WL/SQRT(1-(WL/WLC)**2)
      IF (HDIMW.EQ.0) GO TO 86
      IF (VDIMW.EQ.0) GO TO 59
      SLOTC=1+(SLOT*WLG)**2/(8*PI*VDIMW*HDIMW**3)
      GO TO 86
   59 CON=1.84118
      SLOTC=1+(SLOT*WLG*CON)**2/(8*(PI*HDIMW/2)**4*(CON**2-1))
      GO TO 86
   86 PRNT1=ABS(ANODP-ANODM)
      PRNT2=ABS(SNODP-SNODM)
      ZANODE=(ANODP+ANODM)/2
      ZSNODE=(SNODP+SNODM)/2
      DLTZA=ABS(ANODP-ANODM)/SLOTC
      DLTZS=ABS(SNODP-SNODM)/SLOTC
   87 SHIFT=(ZANODE-ZSNODE)/SLOTC
      DE=ZANODE+RDIMW
      DET=0
   88 DET=DET+WLG/2
      IF (ABS(DE-DET).GE.WLG/4) GO TO 88
      DE=DET
      IF (ADB.EQ.0) ADB=3
      ARG=0.2302585*ADB
      POWER=EXP(ARG)
      VSWR=SQRT(POWER-COS(PI*DLTZA/WLG)**2)/SIN(PI*DLTZA/WLG)
      IF (SDB.EQ.0) SDB=3
      ARG=0.2302585*SDB
      POWER=EXP(ARG)
      ARG=SQRT((POWER-1)/(VSWR**2-1))
      DLTZA=WLG*ARSIN(ARG)/PI
      RATIO=(DE-DDIMS-SHIFT)/DE
   95 PHIPR=PI*(DLTZS-RATIO*DLTZA)/WLG
      VSWR=SQRT(POWER-COS(PHIPR)**2)/SIN(PHIPR)
      PHI=1/VSWR
  100 ZO=-(SHIFT+DDIMS)
      IF (ZO.GE.0) GO TO 102
  101 ZO=ZO+WLG/2
C  I.E.  ADD HALF-WAVELENGTHS UNTIL ZO BECOMES POSITIVE.
      IF (ZO) 101,102,102
  102 U=2*PI*ZO/WLG
      TNU=TAN(U)
      IF (HDIMW.GT.0) P=(WL/WLC)**2
      IF (HDIMW.EQ.0) P=0
      Q=WLG/(2*PI*DDIMS)
      S = WL/(2*PI*DDIMS)
      DEN= Q/(1+(PHI*TNU)**2)
      A=TNU*(PHI**2-1)
      B=PHI*(1+TNU**2)
      C = SQRT(A*A+B*B)*DEN
      C1=C*SIGN(1.0,A)
      UO=A*DEN
      VO=-B*DEN
C  ESTX IS THE FIRST ESTIMATE OF B2D, COMPUTED FROM E' FOR THE
C     APPROPRIATE GUIDE WITH A2D=0.
      IF (ESTDC.EQ.0) ESTDC=ESTEPM
      ESTX = SQRT(ESTDC-P)/S
C
C  KWAD CORRESPONDS TO THE QUADRANT INTO WHICH ESTX (IN RADIANS) FALLS.
  104 KWAD= 1
      IF (ESTX.GT.PI) ESTX = ESTX-PI
    2 IF (ESTX.LT.KWAD*PI/2) GO TO 5
      KWAD=KWAD+1
      GO TO 2
C  SOLUTIONS DO NOT EXIST IN THE FIRST QUADRANT IF C.LT.1.
    5 IF (KWAD-1) 6,6,40
    6 IF (C1.LE.1) ESTX=ESTX+PI
C
C  FIND THREE VALUES OF B2D AND A2D.
   40 ESTXO=ESTX
      DO 42 I=1,3
   42 DIFF(I)=0
      IF (ABS(TNU).GT.200) GO TO 230
      DO 110 I=1,3
      B2D=FINDX(C1,ESTX)
      ESTX=B2D+PI
  105 A2D=(Q*B2D*PHI*(1+TNU**2))/((1+TAN(B2D)**2)-TAN(B2D)/B2D)
      IF (I-1) 106,106,107
  106 TB2D=B2D
      TA2D=A2D
  107 CALL ADJUST (A2D,B2D,UO,VO,I,DIF)
      IF (DIF.LT.0.0002) GO TO 10B
      DIFF(I)=DIF
  108 ALPHA(I)=A2D
      BETA(I)=B2D
  110 CONTINUE
  116 IF (HDIMW.EQ.0) GO TO 200
C
C  CALCULATE 3 DIELECTRIC CONSTANTS, LOSS FACTORS, AND LOSS TANGENTS
C      FOR CIRCULAR OR RECTANGULAR WAVEGUIDES.
      DO 140 I=1,3
      DC(I) = P-S**2*(ALPHA(I)**2-BETA(I)**2)
      FACTOR(I) = S**2*2*ALPHA(I)*BETA(I)
      ALT(I)=FACTOR(I)/DC(I)
      LTW=(1-P)*DLTZA/DE
      IF (VDIMW.EQ.0) GO TO 132
      LTWS=LTW*(HDIMW/(2*VDIMW)+P/DC(I))/(HDIMW/(2*VDIMW)+P)
      GO TO 135
  132 LTWS=LTW*(0.42+P/DC(I))/(0.42+P)
  135 ALT(I)=ALT(I)-LTWS
      FACTOR(I)=ALT(I)*DC(I)
  140 COND(I) = .55668*FACTOR(I)*FREQ
      GO TO 350
C
C  CALCULATE 3 DIELECTRIC CONSTANTS, LOSS FACTORS, AND LOSS TANGENTS FOR
C      COAXIAL LINES.
  200 DO 220 I=1,3
      DC(I)=S**2*(BETA(I)**2-ALPHA(I)**2)
      FACTOR(I)=S**2*2*ALPHA(I)*BETA(I)
      ALT(I)=FACTOR(I)/DC(I)
      LTWS=DLTZA/DE
      ALT(I)=ALT(I)-LTWS
      FACTOR(I)=ALT(I)*DC(I)
  220 COND(I) = .55668*FACTOR(I)*FREQ
      GO TO 350
  230 DATA=1
      DO 231 I=1,3
      B2D=FINDX(C1,ESTX)
      DC(I)=P+(WL*B2D/(2*PI*DDIMS))**2
  231 ESTX=B2D+PI
      DO 232 I=1,3
      ALT(I)=0
  232 FACTOR(I)=0
C
C  PRINT COMPLETE RESULTS IF ALCALC IS OTHER THAN ZERO.
  350 IF (ALCALC.EQ.0) GO TO 380
      WRITE(IRITE,375) SAMPL,J,DATE,MC
  375 FORMAT(1H0,'  DIELECTRIC PROPERTIES FOR ',10A4,//3X,'RUN',I4,5X,2A
     *4///,' MOISTURE CONTENT',31X,A4)
      WRITE(IRITE,376) TF,F,HDIMW,VDIMW,DDIMS,ZANODE,ZSNODE, ADB,PRNT1,
     * SDB,PRNT2,RDIMW,ESTDC
  376 FORMAT(1H ,'TEMPERATURE (DEGREES FAHRENHEIT)',12X,A5/' FREQUENCY (
     *GIGAHERTZ)',F33.4,/' WAVEGUIDE HORIZONTAL DIMENSION (MM)',F19.4,/'
     * WAVEGUIDE VERTICAL DIMENSION (MM)',F21.4,/' SAMPLE LENGTH (MM)',F
     *36.4,/' AIR NODE POSITION (MM)     ',F28.4,/' SAMPLE NODE POSITION
     *(MM)',F29.4/' AIR NODE WIDTH (MM)',F11.1,  ' DB  ',F19.4,  /' SAMP
     *LE NODE WIDTH (MM)',F 8.1,' DB',F21.4,/'            REFERENCE DIMEN
     *SION (MM)',F20.4,/' ESTIMATED DIELECTRIC CONSTANT',F25.4)
      IF (DATA.EQ.0.0) GO TO 373
      SDC(J)=0
      SLT(J)=0
      SFACT(J)=0
      SCOND(J)=0
      ESTEPM=ESTDC
      WRITE(IRITE,371) TNU
  371 FORMAT(1H0,'BAD SAMPLE LENGTH FOR THIS FREQUENCY, NEARLY AN ODD MU
     *LTIPLE QUARTER WAVELENGTH.',/,' TANGENT((2*PI*ZO)/WLG) =',F10.3)
      WRITE(IRITE,372) (DC(I),I=1,3)
  372 FORMAT(1H ,'DIELECTRIC CONSTANT',3F15.6,1H1)
      GO TO 380
  373 WRITE(IRITE,374) ESTXO
  374 FORMAT(1H ,'FIRST ESTIMATE OF B2D (ESTX)',F26.4/)
      WRITE(IRITE,382) TA2D, TB2D
      WRITE(IRITE,383) ALPHA(1), BETA(1)
  382 FORMAT(1H ,'UNADJUSTED A2D, B2D ',2F20.5)
  383 FORMAT(1H ,'ADJUSTED A2D, B2D   ',2F20.5//)
      WRITE(IRITE,377)SAMID
  377 FORMAT(18X,'  SAMPLE  ',2A4,'  RESULTS  '/)
      WRITE(IRITE,378) (DC(I),I=1,3),(ALT(I),I=1,3),(FACTOR(I),I=1,3), (
     *CONC(I),I=1,3)
  378 FORMAT(' DIELECTRIC CONSTANT',5X,3F15.6,/' LOSS TANGENT',12X,  3F1
     *5.6,/' LOSS FACTOR ',12X,3F15.6,/' CONDUCTIVITY',12X,3F15.6)
      DO 379 I=1,3
      IF (DIFF(I).EQ.0) GO TO 379
      WRITE(IRITE,1100) DIFF(I),I
 1100 FORMAT(1H0,'DIFF1=',F10.6,' FOR ESTIMATE NO.',I3/)
  379 CONTINUE
      WRITE(IRITE,1200)
C   ADD TO SUMMARY TABLE PROBABLE DC AND LOSS-TAN VALUES
  380 KOUNTR=1
      DELTA=ABS(DC(1)-ESTDC)
      DO 320 I=2,3
      GUESS=ABS(DC(I)-ESTDC)
      IF (GUESS-DELTA) 360,360,320
  360 KOUNTR=I
      DELTA=GUESS
  320 CONTINUE
      ESTEPM= DC(KOUNTR)
  321 SDC(J)=DC(KOUNTR)
      SLT(J) = ALT(KOUNTR)
      SFACT(J) = FACTOR(KOUNTR)
      SCOND(J) = .55668*FACTOR(KOUNTR)*F
  322 SF(J) = F
      SMC(J)=MC
      STF(J) = TF
      DO 400 N=1,2
      SDAY(J,N) =DATE(N)
  400 SSMP(J,N) = SAMID(N)
C   WRITE SUMMARY TABLE
  405 WRITE(IRITE,410) SAMPL
  410 FORMAT(1H0,'DIELECTRIC PROPERTIES FOR ',10A4///)
      WRITE(IRITE,412)
  412 FORMAT(34X,'SUMMARY TABLE'//'   DATE    MOIST TEMP   SAMPLE   FREQ
     *. DIELECTRIC  LOSS   LOSS   CONDUCTIVITY'/11X,'CONT. (F.)   IDENT.
     *   (GHZ)  CONSTANT  FACTOR TANGENT MILLIMHOS/CM'/)
      DO 414 J=1,JJ
  414 WRITE(IRITE,415) (SDAY(J,N),N=1,2),SMC(J),STF(J),(SSMP(J,N),N=1,2)
     *,SF(J),SDC(J),SFACT(J),SLT(J),SCOND(J)
  415 FORMAT(1H ,2A4,3(2X,A4),A4,F7.3,F9.4,2F8.4,F12.4)
  500 CONTINUE
      CALL EXIT
      END
```

```
FORTRAN IV G LEVEL  19                  ADJUST

      SUBROUTINE ADJUST(A2D,B2D,U0,V0,I,DIFF1)
      J=0
      DELTA=0.01
      CALL ACOMP(UA,VA,A2D,B2D)
      DIFF1=SQRT((U0-UA)**2+(V0-VA)**2)
    5 IF (DIFF1.LT.0.0002) RETURN
   10 K=0
      TA2D=A2D+DELTA
   15 CALL ACOMP(UA,VA,TA2D,B2D)
      DIFF2=SQRT((U0-UA)**2+(V0-VA)**2)
      K=K+1
      IF (DIFF2-DIFF1) 20,25,25
   20 A2D=TA2D
   22 DIFF1=DIFF2
      GO TO 5
   25 IF (K-1) 30,30,40
   30 TA2D=A2D-DELTA
      GO TO 15
   40 K=0
      TB2D=B2D+DELTA
   45 CALL ACOMP(UA,VA,A2D,TB2D)
      DIFF2=SQRT((U0-UA)**2+(V0-VA)**2)
      K=K+1
      IF (DIFF2-DIFF1) 50,55,55
   50 B2D=TB2D
      GO TO 22
   55 IF (K-1) 60,60,80
   60 TB2D=B2D-DELTA
      GO TO 45
   80 DELTA=DELTA/2
      J=J+1
      IF (J-13) 10,90,10
   90 RETURN
      END
```

```
FORTRAN IV G LEVEL  19                  ACOMP

      SUBROUTINE ACOMP (UA,VA,A2D,B2D)
      X=A2D*2
      Y=B2D*2
      V1=A2D*SINH(X)+B2D*SIN(Y)
      V2=A2D*SIN(Y)-B2D*SINH(X)
      BOT=(A2D**2+B2D**2)*(COSH(X)+COS(Y))
      UA=V1/BOT
      VA=V2/BOT
      RETURN
      END
```

```
FORTRAN IV G LEVEL  19                 FINDX

          FUNCTION FINDX (C,ESTX)
          K=1
          PI=3.141592654
          X0=ESTX
          NSTOP=0
     10   IF (ESTX.LT.K*PI/2) GO TO 20
          K=K+1
          GO TO 10
     20   TEST=TAN(ESTX)/ESTX
          IF (C*TEST.GT.0.0) GO TO 21
          IF (ABS(C).GT.2.0) GO TO 30
     21   DO 26 N=1,10
          IF (K-(2*N-1)) 25,22,26
     22   IF (K-1) 23,23,24
     23   A=0
          B=PI/2
          GO TO 40
     24   B=K*PI/2
          A=B-PI
          GO TO 40
     25   A=(K-1)*PI/2
          B=A+PI
          GO TO 40
     26   CONTINUE
     30   IF (C) 31,32,32
     31   ESTX=K*PI-ESTX
          A=K*PI/2
          B=A+PI
          GO TO 40
     32   ESTX=(K-1)*PI-ESTX
          B=(K-1)*PI/2
          IF (K-2) 33,33,34
     33   A=0
          GO TO 40
     34   A=B-PI
     40   X1=ESTX
     50   DELTA=X1*(TAN(X1)-C*X1)/(X1/COS(X1)**2-TAN(X1))
          X2=X1-DELTA
          NSTOP=NSTOP+1
          IF (X2.LT.A) GO TO 60
          IF (X2.GE.B) GO TO 60
          IF (ABS(DELTA).LE.0.0001) GO TO 80
          X1=X2
          GO TO 70
     60   IF (C.GT.0) ESTX=(ESTX+B)/2
          IF (C.LE.0) ESTX=(ESTX+A)/2
          X1=ESTX
     70   IF (NSTOP.EQ.75) GO TO 90
          GO TO 50
     80   FINDX=X2
          RETURN
     90   FINDX=X0
          WRITE(6,102)
    102   FORMAT(1H ,'FINDX=X0'/)
          RETURN
          END
```

Data form for short-circuited waveguide measurements with examples of data recorded for rectangular, cylindrical, and coaxial waveguide measurements corresponding to data for figs. 5 through 8. The last column is for the sample density.

SHORT-CIRCUITED LINE OR WAVEGUIDE MEASUREMENTS FOR DIELECTRIC PROPERTIES COMPUTATION

Sample description (40)
1970 Scout 66 HRW Wheat

Date 7/30/71 Moist. cont. 10.5 % Temp. 76°F

Equipment	Waveguide dim.		Ref. dim.	λ_c
X-Band	22.86	10.16	(130), 120	45.720
CRL Cylindr.	25.45		0, 150, (300)	43.425
Coaxial			0, 150, 300	
R&S Coaxial			150	

Slot width
3.2 mm
1.24

$f = 299.6966/\lambda_o$

$1/\lambda_o^2 = 1/\lambda_g^2 + 1/\lambda_c^2$

Sample holder constants

60.03 mm, 2.323 cm²,	4.306 mm/ml
5.087	1.966
4.379	2.284
2.810	3.559

Sample ident. (8)	Frequency GHz	Air node readings mm		Sample node readings mm		Sample length mm	dB level		Est. ε'_r	Remarks	ε'_r	ε''_r	tan δ	σ mmhos	ρ
							Air	Samp.							
3-3	8.388	13.542	13.833	19.13	25.43	34.8	6	3	2.7		2.624	0.241	0.092	1.12	0.800
3-3	10.186	4.896	4.967	14.91	28.17	35.0	6	0.8	2.7		2.600	0.258	0.099	1.46	0.795
3-3	11.030	22.491	22.562	22.14	26.82	35.0	6	3	2.7		2.586	0.278	0.108	1.71	0.795
3-3	12.228	15.684	15.599	14.71	25.52	36.4	6	2	2.7		2.517	0.214	0.085	1.46	0.764
freq.		61.123	61.212	91.182	91.277					f= 8.5144					
3-1		61.123	61.212	75.30	84.62	46.0	3	3	2.7		2.642	0.205	0.078	0.97	0.799
freq.		60.23	60.15	121.65	121.78										
3-2		94.70	94.80	69.10	72.92	38.3	3	3	2.7	f= 2.4356	2.633	0.261	0.099	0.35	0.796